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14. ABSTRACT
The objective of this project was to theoretically develop and validate the principles, metrics, and algorithms to achieve intra-pulse radar-embedded communications for covert high data throughput. From a "forward link" perspective, the pulse-agile radar paradigm has been explored where a radar may use different waveforms within a coherent processing interval to represent different broadcast communication symbols thereby enabling "dual use" emissions. The main focus of this effort was to alleviate the performance degradation that occurs for the radar when operated in this manner. Alternatively, from a "reverse link" perspective a new form of spread spectrum communications was developed where the symbols are designed to be partially correlated with the radar waveform so that they can be adequately hidden within the radar backscatter (or clutter). The major results here were the development of a new form of receiver symbol estimation/detection and the theoretical analysis of processing gains for the desired and intercept receivers to establish a "gain advantage" metric with which to optimize the parameterization of symbol design.

15. SUBJECT TERMS
radar, communications, low probability of intercept, waveform diversity, interference cancellation

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Final Report

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General Program Overview

The objective of this project was to theoretically develop and validate the principles, metrics, and algorithms to achieve *intra*-pulse radar-embedded communications for covert high data throughput. From a “forward link” perspective, the pulse-agile radar paradigm has been explored where a radar may use different waveforms within a coherent processing interval to represent different broadcast communication symbols thereby enabling “dual use” emissions. This form of transmit diversity induces a degradation of radar clutter cancellation performance and, as such, a new framework for the design radar pulse compression filtering was devised that seeks to constrain the range ambiguity of each waveform/filter pair to be identical.

Alternatively, from a “reverse link” perspective a new form of spread spectrum communications was developed where the symbols are designed to be partially correlated with the radar waveform so that they can be adequately hidden within the radar backscatter (or clutter). For this paradigm a symbol design approach was developed that is robust to timing jitter and multipath. It was found that the spatial focusing benefit of time reversal is readily amenable to this form of communication. To compensate for the lack of a control channel, a two-stage symbol detector was developed for the receiver that compensates for the lack of synchronization and establishes a maximum acceptable symbol error rate by statistically measuring the confidence in a given symbol selection. Additionally, theoretical analysis of the processing gains for both the desired receiver and a hypothetical worst-case intercept receiver has realized a “gain advantage” design metric for symbol parameter optimization.

“Reverse Link” Operation

This aspect of the project explored the notion of intra-pulse radar-embedded communication in which an RF tag/transponder (henceforth simply referred to as the “tag”) is within the field of illumination of a pulsed radar system [1,2,4]. The tag either remodulates the incident radar illumination (or transmits upon being triggered) to produce a communication symbol that is hidden within the radar backscatter (clutter). The three major aspects of this effort have been the theoretical and pragmatic investigation of 1) communication symbol design, 2) design of the desired receiver, and 3) assessment of possible intercept receiver performance. The following highlights the important results for each of these.

Communication Symbol Design

To exploit the presence of radar clutter within which to hide a low probability of intercept (LPI) communication signal, the design of appropriate communication symbols is of paramount importance. The symbols must be sufficiently similar to the clutter so as to remain covert yet the desired receive must be able to extract the embedded symbol with sufficient accuracy. Thus, since the clutter is “colored” by the illuminated radar waveform $s(t)$, the clutter can be generically modeled as

$$y_{\mathrm{s}}(t) = s(t) * x(t) \tag{1}$$

where $x(t)$ is the arbitrary (and unknown) clutter impulse response in the neighborhood of the tag. Discretizing $s(t)$ and $x(t)$ as $\mathbf{s}$ and $\mathbf{x}$, respectively, and assuming the clutter is uncorrelated in range (i.e. $E[\mathbf{x}\mathbf{x}^H] = \sigma_x^2 \mathbf{I}$ for σ_x^2 the average clutter power), communication symbols may be obtained by exploiting via manipulation of subspaces of the normalized correlation matrix

$$\frac{1}{\sigma_x^2} E\left[(\mathbf{Sx})(\mathbf{Sx})^H\right] = \mathbf{SS}^H = \mathbf{V\Lambda V}^H \tag{2}$$

where $\mathbf{S}$ contains sample-shifted versions of $\mathbf{s}$ in the columns, while $\mathbf{V}$ and $\mathbf{\Lambda}$ contain the resulting eigenvectors and their associated eigenvalues, respectively.

Oversampling the tag-incident radar waveform $s(t)$ above Nyquist by some factor M produces an eigen-decomposition in (2) containing a dominant subspace and a non-dominant sub-space (the exact boundaries of which can be obtained via optimization as will be discussed shortly). In reality, the simplification of the middle step of (2) may not be precisely obtained due to imperfect synchronization of the sampling of $s(t)$ (between the tag and desired receiver), forward scattering effects (multipath), and noise, which could result in (potentially significant) symbol mismatch between the tag and intended receiver. Because the eigen-decomposition is quite sensitive to change (particularly for the smallest eigenvalues), the symbol design framework must be robust to perturbations within $\mathbf{V}$ and $\mathbf{\Lambda}$. It was found that a projection-based approach meets this criterion such

that the set of K symbols $\mathbf{c}_k$ for $k = 1, 2, \cdots, K$ are obtained as $\mathbf{c}_k = \mathbf{P}\mathbf{b}_k$ where $\mathbf{b}_k$ are seed vectors known to both the tag and desired receiver and

$$\mathbf{P} = \mathbf{I} - \mathbf{V}_D \mathbf{V}_D^H = \mathbf{V}_{ND} \mathbf{V}_{ND}^H \tag{3}$$

such that the K symbols are projected onto the non-dominant subspace ($\mathbf{V}_{ND}$), which is the orthogonal complement of the dominant subspace $\mathbf{V}_D$ with $\mathbf{V} = \left[\mathbf{V}_D \ \mathbf{V}_{ND}\right]$. It was shown analytically in [6] that robustness to symbol mismatch can be maintained as long as the separation between the dominant and non-dominant subspaces is preserved. As an example, Figure 1 illustrates the average correlation over 1000 Monte Carlo trials of the eigenvector matrices resulting from corruption of the radar waveform $s(t)$ by two independent multipath channels $h_1(t)$ and $h_2(t)$, where each contains 10 components randomly distributed in time, amplitude, and phase. Despite this corruption it is observed that the dominant and non-dominant subspace remain largely separate thus ensuring minimal symbol mismatch. For all practical purposes, this form of communication is only possible if this condition is met. Variations on this design approach have also been explored [17].

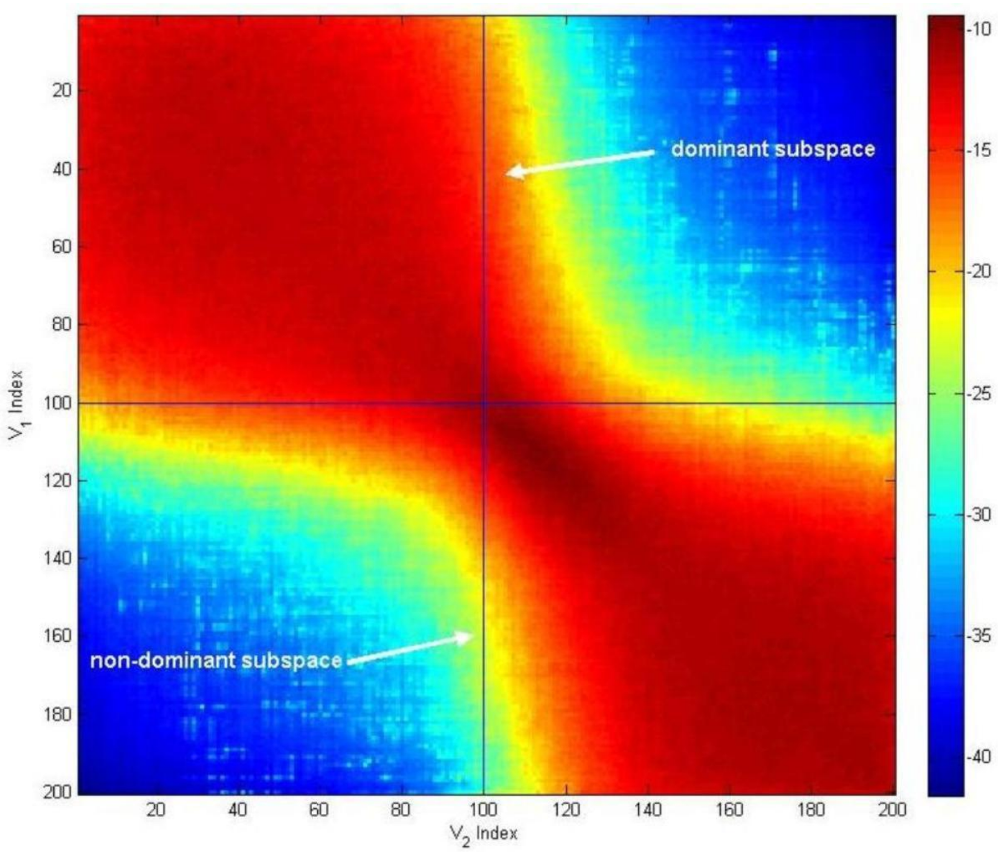


Figure 1. Average correlation (1000 trials) between eigenvector sets generated from radar waveform distortion by independent multipath channels (dB scale)

While it is necessary to design the communication symbols in a way that is robust to forward scattering effects, the nature of this communication paradigm also makes it amenable to exploitation of the multipath through the use of time-reversal [6,13]. Assuming reciprocity holds, the multipath channel $h(t)$ between the radar and tag is identical in both directions. Thus if $h(t)$ can be estimated at the tag then it can be incorporated into the communication symbols to exploit the spatio-temporal focusing benefits of time-reversal to improve error performance at the receiver and/or improve LPI performance. In the case that the tag possesses *a priori* knowledge of the radar illumination, multipath estimation can easily be performed via standard matched filtering at the tag. However, in the case where the radar illumination is not known to the tag, some form of blind channel estimation is required. To that end, a robust method of direction of arrival (DoA) estimation was developed [5] that incorporates limitations on array manifold knowledge. Under the assumption that different multipath delayed replicas of the radar waveform arrive from different spatial directions, this DoA technique subsequently enables a degree of blind channel estimation [16].

Finally, the determination of the boundary between the dominant and non-dominant subspaces impacts the performance of both the desired receiver and an intercept receiver. An optimization metric was derived for the *gain advantage* of the desired receiver over a hypothetical worst-case intercept receiver. For m the rank of the dominant subspace employed to design the K communication symbols and n the dominant subspace rank of the projection-based interference canceller used by a hypothetical intercept receiver (that scans over all values of n), the metric [6]

$$\Psi(m,n) \geq \frac{\left(NM - m\right)\left(\sigma_x^2 \,\mathrm{tr}\left\{\mathbf{\Lambda}_{ND,n}\right\} + \sigma_u^2\left(NM - n\right)\right)}{\left(NM - \max\left\{m,n\right\}\right)\left(\sigma_x^2\, \lambda_{m+1} + \sigma_u^2\right)} \tag{4}$$

can be optimized according to

$$\max_m \min_n \Psi(m,n) \tag{5}$$

where σ_u^2 is the noise power, λ_{m+1} is the largest non-dominant eigenvalue for symbol design, and NM is the time-bandwidth product used for symbol design. An example of the metric in (4) is shown in Fig. 3 for a clutter to noise ratio (CNR) of 30 dB. The resulting value of m provides, according to the spectral content of the radar illumination, the boundary between the dominant and non-dominant subspaces for symbol design that provide the highest gain advantage for the desired receiver over all possible parameterizations by the hypothetical intercept receiver.

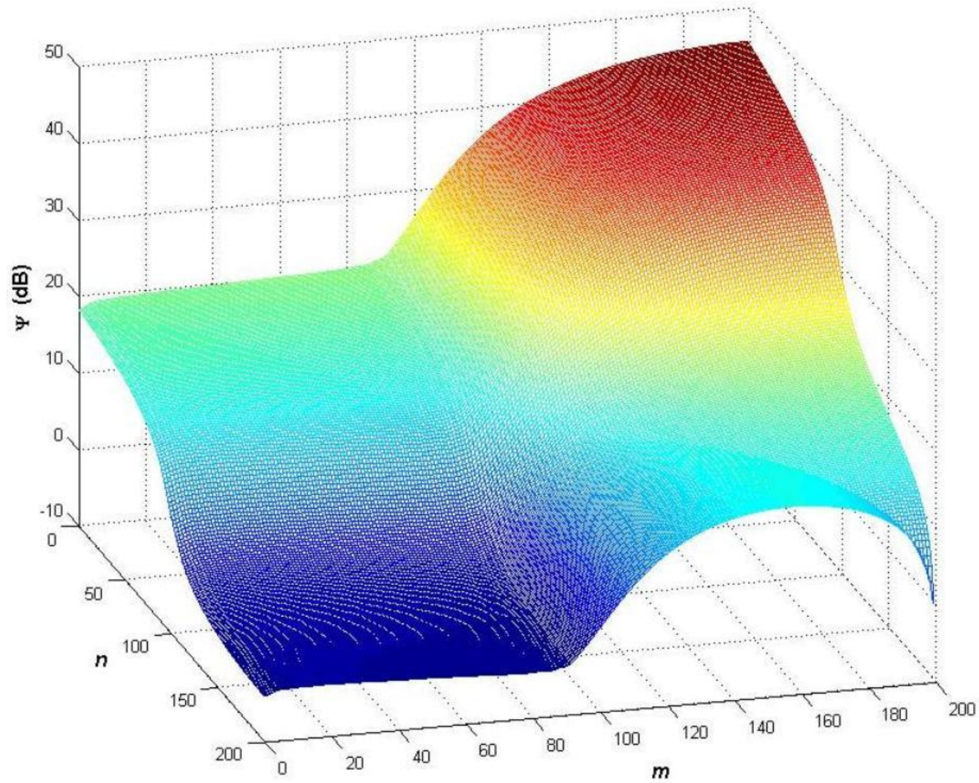


Figure 3. Example depiction of the gain advantage Ψ according to symbol design parameter (*m*) and intercept receiver search parameter (*n*)

<u>*Receiver Design*</u>

For the desired receiver to extract the communication symbol embedded in clutter and noise it must perform coherent integration (hence the requirement to minimize symbol mismatch), interference cancellation (in the range domain), and finally symbol estimation to select the most likely symbol present. Note that this communication paradigm employs no form of a *control channel* and thus the receiver has no *a priori* knowledge of the arrival time of a symbol or even if a symbol is present. Therefore the receiver must adequately suppress the clutter and search through the resulting residue for each of the K possible symbols. Denoting the vector $\mathbf{y}(\ell)$ as a discretized segment of the received signal at time delay ℓ having the same time support as a possible symbol, the received signal can be modeled as belonging to one of the $K + 1$ hypotheses

$$\begin{aligned} &\mathcal{H}_0 :\ \mathbf{y}(\ell) = \mathbf{S}\tilde{\mathbf{x}} + \mathbf{u} \\ &\mathcal{H}_k :\ \mathbf{y}(\ell) = \mathbf{S}\tilde{\mathbf{x}} + \alpha \mathbf{c}_k + \mathbf{u} \quad \text{for } k = 1, 2, \cdots, K , \end{aligned} \tag{6}$$

where $\tilde{\mathbf{x}}$ is a new arbitrary clutter profile, α subsumes the transmit strength of the tag and one-way attenuation, and $\mathbf{u}$ contains samples of noise. Based on (6) and under the assumption that the K symbols have relatively low cross-correlation, the two-stage symbol estimator/detector shown in Fig. 3 was developed [6,9]. This decision rule employs maximum likelihood (ML) symbol estimation via the bank of filters ($\mathbf{w}_k$ for

$k = 1, 2, \cdots, K$) and subsequent sorting according to the magnitude of filter residues to select the most likely symbol present over the entire receiver interval. A Neyman-Pearson (NP) detector is then used to assess the confidence in this symbol selection where the filter residues associated with the unselected $K-1$ symbols are used to estimate the variance of the null hypothesis.

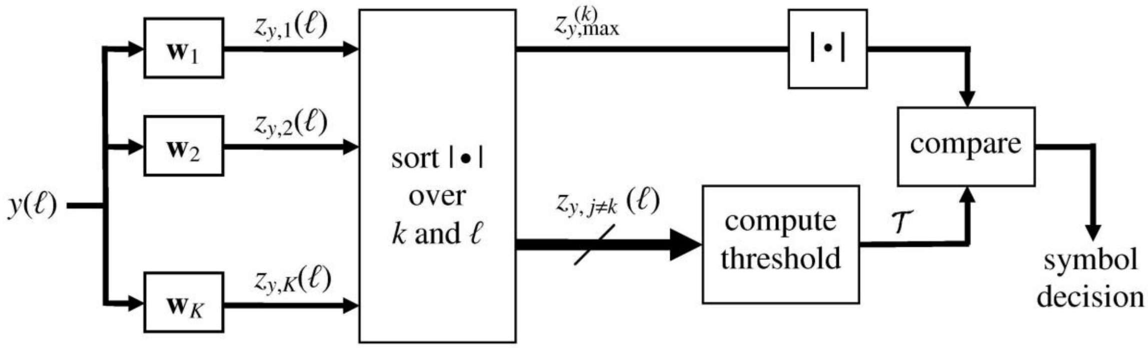
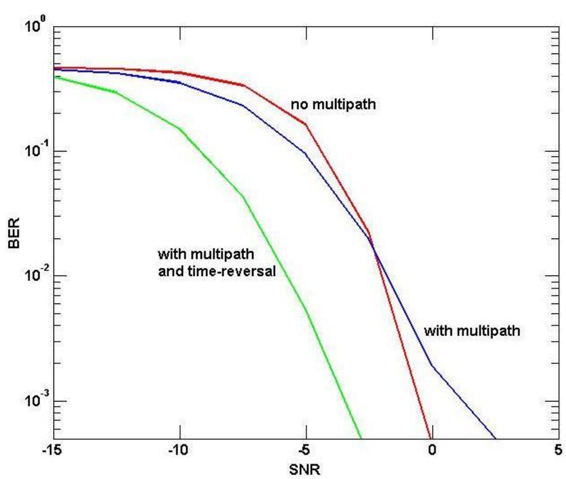
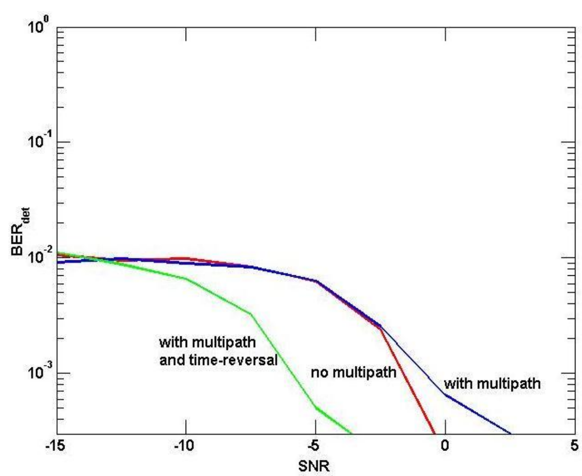


Figure 3. Signal flow of decision rule for symbol detection/estimation

Note that, for the decision rule above, if a selected symbol does not pass the NP detector then no symbol selected. As a result, the receiver bit error rate (BER) can be maintained at or below a prescribed value due to the fact that the received data rate is now dependent upon the SINR of the embedded symbol. Furthermore, this decision rule has the additional benefit of providing an automatic synchronization capability. Figure 4 compares the BER without and with the NP detector, where the latter provides a maximum BER of 10^{-2}, even at low SNR. It is also observed in Fig. 4 that while multipath has only a minor effect on receiver performance, if time-reversal is employed for symbol design in the tag a significant performance gain can be obtained. The impact of receiver-deleted symbols is shown in Fig. 5 via the probability of miss.



(a)



(b)

Figure 4. Bit error rate for 30 dB CNR using (a) only ML estimation and (b) ML estimation followed by the NP detector

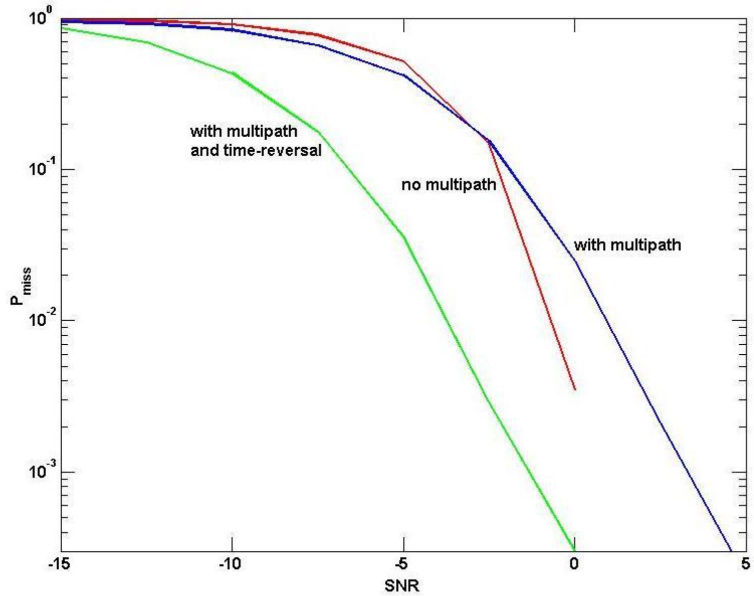


Figure 5. Probability of not detecting the correctly selected symbol

Finally, for the received signal model of (6) and use of the ML receive filters $\mathbf{w}_k$ for $k = 1, 2, \cdots, K$, it has been analytically shown [6] that the processing gain is

$$\Delta(m) = \frac{SINR_o}{SINR_i} \geq NM\left(\frac{\sigma_x^2 + \sigma_u^2}{\sigma_x^2 \lambda_{m+1} + \sigma_u^2}\right), \tag{7}$$

where $SINR_i$ and $SINR_o$ are the signal to interference plus noise ratio before and after receive filtering, respectively. It is interesting to consider this processing gain (which includes clutter cancellation) in light of traditional spread spectrum coherent integration as illustrated in Fig. 6. Whereas the traditional processing gain would be NM for this scenario, the presence of clutter interference and its subsequent cancellation allows the processing gain here to achieve, at maximum, $(NM)^2$. Of course, this extreme is unlikely to be completely achieved once the intercept receiver performance is considered, the combination of which yields the gain advantage metric in (4).

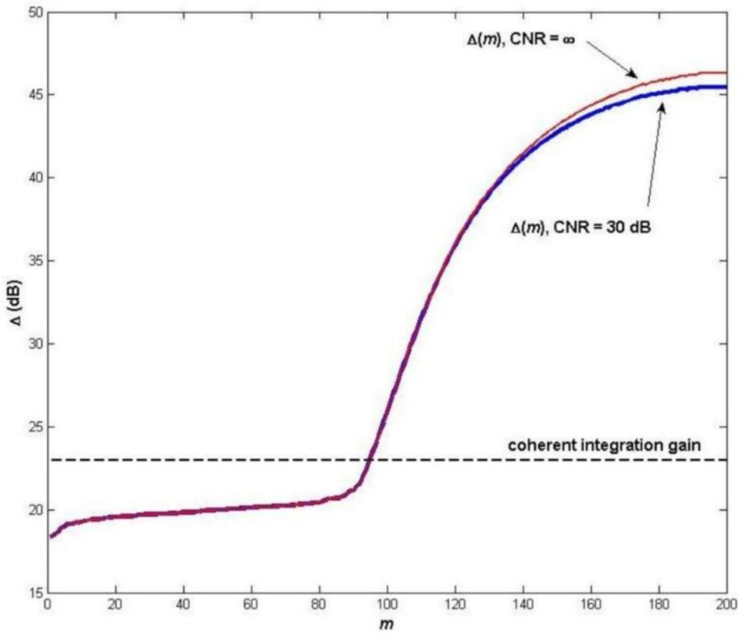


Figure 6. Processing gain as a function of dominant subspace rank *m* for *NM* = 200

Intercept Metric

Traditional spread spectrum techniques attempt to hide the signal energy in noise either through spreading (CMDA) or hopping (FHSS). In contrast, this new form of LPI communication exploits the location dependence of another man-made signal, namely radar, to hide the communication signal. Given the scenario of a distant desired receiver and a nearby intercept receiver (a form of the *near-far problem*), the advantage of radar-embedded communication is clear. That said, the presence of clutter as well as the tag's intent to remain sufficiently similar to the clutter greatly complicates the analysis of the intercept probability. As such, a hypothetical intercept metric has been developed that, because it makes use of clairvoyant knowledge of the communication symbol parameterization (namely, its time-bandwidth product), is conjectured to represent the best performance an intercept receiver could possibly achieve for a fixed false alarm rate.

An intercept receiver is not privy to the *K* symbols but could still be capable of performing range-domain clutter cancellation by forming a projection matrix in the same way as in (2) and (3) based on the observed radar illumination. Thus an intercept metric can be expressed as [6,9]

$$\varepsilon_{ir}(n,\ell) = \mathbf{y}^H(\ell)\,\mathbf{P}_n\,\mathbf{y}(\ell)\,, \tag{8}$$

which is a function of delay ℓ and the rank n of the dominant subspace used to form the intercept projection matrix

$$\mathbf{P} = \mathbf{I} - \mathbf{V}_{D,n}\mathbf{V}_{D,n}^H = \mathbf{V}_{ND,n}\mathbf{V}_{ND,n}^H\,. \tag{9}$$

By varying the value of n the hypothetical intercept metric provides a means to search over the various subspaces where the communication symbol could exist. Applying the central limit theorem it can be shown that (8) is distributed as the sum of $NM-n$ independent exponential distributions, the rates of which are the diagonal elements of $\left[\sigma_x^2 \mathbf{\Lambda}_{\mathrm{ND},n} + \sigma_u^2 \mathbf{I}_{(NM-n)}\right]$. Thus for a given probability of false alarm, a threshold can be numerical computed for this metric.

Similar to (7), a processing gain for this hypothetical intercept metric was found to be [6]

$$\Delta_{ir}(n;m) = \frac{SINR_{ir}}{SINR_i} = \frac{(NM - \max\{m,n\})(\sigma_x^2\, NM + \sigma_u^2 NM)}{(NM-m)(\sigma_x^2\, \mathrm{tr}\{\mathbf{\Lambda}_{\mathrm{ND},n}\} + \sigma_u^2 (NM-n))}, \tag{10}$$

where $SINR_{ir}$ is the signal to interference plus noise ratio after the intercept receiver applies the metric (8). The gain advantage of (4) is obtained by combining the respective processing gains from (7) and (10) as

$$\Psi(m,n) = \frac{\Delta_i(m)}{\Delta_{ir}(n;m)}, \tag{11}$$

which, for the purpose of symbol parameterization, provides a means to determine the symbol subspace rank m for which the smallest gain advantage (over n) is maximized. For example, using an optimized symbol rank, Fig. 7 illustrates the performance advantage of the desired receiver (with and without multipath and time-reversal) over this hypothetical "worst case" intercept receiver metric (blue curve on the right).

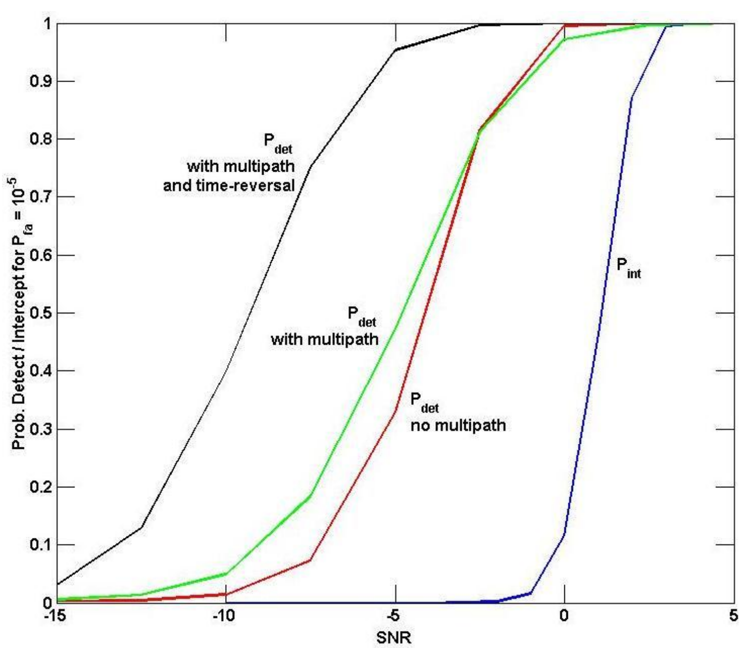


Figure 7. Probability of symbol detection and interception

"Forward Link" Operation

In contrast to the "reverse link" operation, for the "forward link" the notion of incorporating information into radar emissions was considered. This mode of operation is not necessarily LPI but instead leverages the radar emissions for a dual-use purpose. This work has also been a component of on-going work to address radar spectral congestion [8]. Furthermore, the incorporation of dual-use emissions into the radar modality is generally detrimental to radar performance if classical receive processing schemes are employed. As such, this effort has primarily focused on how to recover radar performance, specifically for the sensing modes of pulse-agile radar and MIMO radar.

<u>*Pulse-Agile Radar*</u>

The pulse-agile radar concept involves transmitting different waveforms on the different pulses in a coherent processing interval (CPI) [12,14]. The dual-use incorporation of a communication aspect to the radar emissions could be accomplished by allowing the waveforms to belong to a set such that each waveform represents a communication symbol. Because the radar is generally a high power transmitter, communication receive processing would effectively require simply a matched filter bank. However, is standard radar receive processing were employed, a severe performance penalty would be incurred due to the range sidelobe modulation of clutter over the CPI, which subsequently hinders clutter cancellation in the Doppler domain and thereby degrades sensitivity.

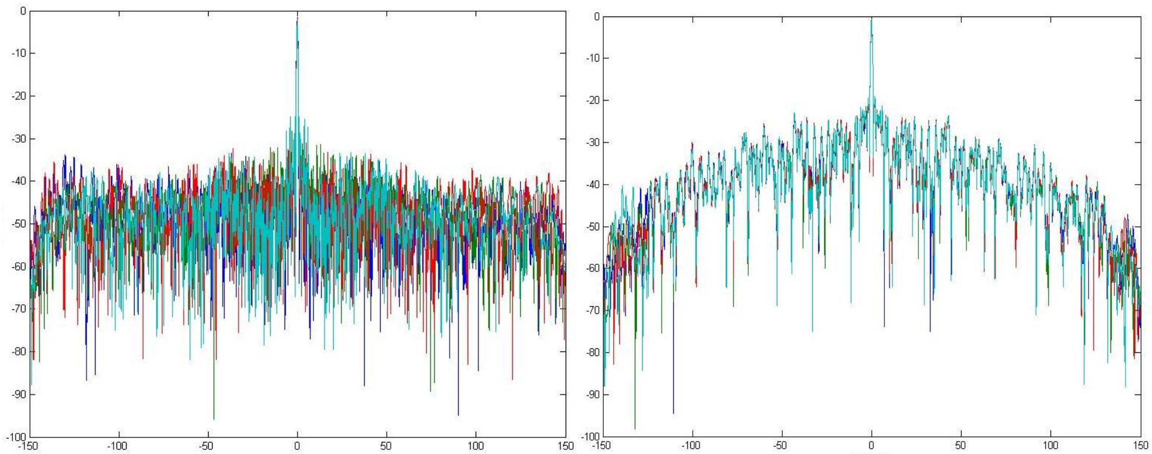
To address this problem a new pulse compression filter design constraint has been conceived in which the range ambiguity is forced to be uniform over all waveform/filter pairs, i.e.

$$s_1(t) * h_1(t) = s_2(t) * h_2(t) = \cdots = s_K(t) * h_K(t) . \tag{12}$$

It has been found that equality can only be met for the $K = 2$ case. For $K > 2$, the filters become mismatched filters and the constraint can only be approximated (due to the resulting requirement for infinite length filters). The primarily difficulty with designing these filters is that besides (approximately) meeting the above constraint, it is also required that the range sidelobes be sufficiently low. Given finite design degrees of freedom, it is clear that a performance penalty will be paid in terms of range sidelobe levels by incorporating this constraint.

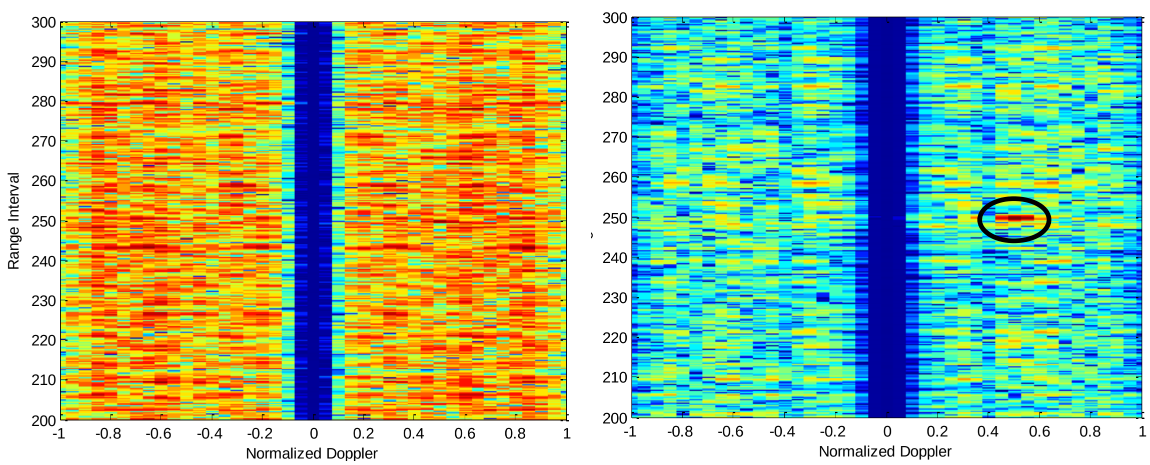
A preliminary approach to design the K filters has been developed according to an ad hoc modification to the well-known least-squares (LS) mismatch filter formulation. This new approach, denoted as joint LS (JLS), iteratively drives the mismatch filters to yield a nearly identical range ambiguity. For example, Fig. 8 shows the waveform/filter correlations for $K = 4$ different waveforms using both standard LS and the new JLS design scheme. It is observed that the latter achieves much better uniformity of range ambiguity, albeit at the cost of higher range sidelobes. That said, simulation results have demonstrated significant improvement of JLS over LS when subsequent clutter

cancellation is employed due to a marked recovery of clutter coherency (e.g. see Fig. 9). The development of an optimal filter design strategy, as well as the incorporation of waveform design [11], remains an open problem.



(a) **(b)**

Figure 8. Waveform/filter correlations for (a) standard LS and (b) JLS filters



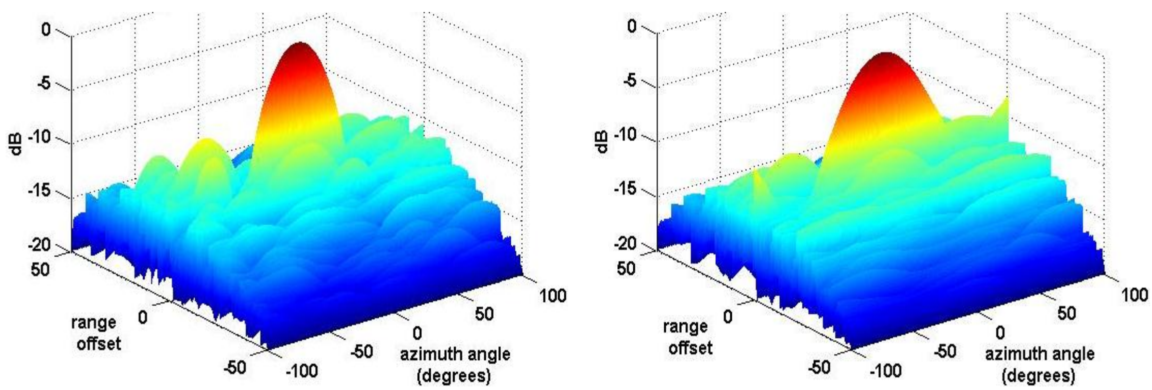
(a) **(b)**

Figure 9. Range-Doppler processing (with clutter cancellation) for (a) standard LS and (b) JLS pulse filters

<u>*MIMO Radar*</u>

The MIMO framework has been proposed for use in both communications and radar and thus it stands to reason that it could hold some interesting possibilities for joint communication/radar. That said, because the general MIMO paradigm employs different (fast time) temporal waveforms on different spatial antenna elements, the impact of the interaction between these domains has been the focus of investigation thus far [3,7]. In particular, this effort has addressed the practical limitations that mutual coupling induces due to the inherent coupling of space and fast-time (range domain for radar) [10].

Preliminary evidence using simplistic modeling for the mutual coupling has indicated that a significant mismatch effect occurs with respect to the idealistic presumed MIMO emissions. For example, Fig. 10 depicts the resolution degradation that occurs for a circular array with a different waveform emitted by each of the 16 elements. The average waveform mismatch loss was observed to be 1.1 dB over 100 Monte Carlo trials and all azimuth directions. The take away from this work is that EM effects need to be incorporated into MIMO modalities that perform sensing or else significant penalties will result in terms of resolution and sensitivity.



(a) **(b)**

Figure 10. Range-angle ambiguity for (a) idealistic and (b) mutual coupling induced mismatch

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Books

1. *Principles of Waveform Diversity & Design*, eds. M. Wicks, E. Mokole, S.D. Blunt, V. Amuso, and R. Schneible, SciTech Publishing, Aug. 2010.

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13. S.D. Blunt and J.G. Metcalf, "Using Time Reversal of Multipath for Intra-Pulse Radar-Embedded Communications," *5th International Waveform Diversity & Design Conference*, Niagara Falls, Canada, 8-13 Aug. 2010.

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19. J. Metcalf, "Detection Strategies and Intercept Metrics for Intra-Pulse Radar-Embedded Communications ," Master's Thesis, University of Kansas, Fall 2011.

20. C. Biggs, "Practical Considerations for Radar Embedded Communications," Master's Thesis, University of Kansas, 1 July 2009, http://kuscholarworks.ku.edu/dspace/bitstream/1808/5450/1/Biggs_ku_0099M_10460_DATA_1.pdf.

Invited Presentations

1. B. Cordill, J. Metcalf, S.A. Seguin, D. Chatterjee, and S.D. Blunt, "The Impact of Mutual Coupling on MIMO Radar Emissions," *IEEE International Conference on Electromagnetics in Advanced Applications*, Turino, Italy, Sept. 12-17, 2011.

2. "Radar-Embedded Communications," *USNC-URSI National Radio Science Meeting*, Boulder, CO, Jan. 5-8, 2011.

3. "Shared-Spectrum Radar / Spectrum Efficient Waveform Implementation," *5th DISA Defense Spectrum Organization - Emerging Spectrum Technology Workshop*, Annapolis, MD, Sept. 13-14, 2010.

4. "Embedding Information into Radar Emissions via Waveform Implementation," *5th International Waveform Diversity & Design Conference*, Niagara Falls, Canada, 8-13 Aug. 2010.

5. "Advanced Signal Processing for Radar Spectrum Management," *Radar Spectrum Workshop at Tri-Service Radar Symposium*, Orlando, FL, June 21-25, 2010.

6. "Radar-Embedded Communications: Ongoing Work and Opportunities," AFRL Sensors Directorate, Dayton, OH, December 16, 2009.

7. S.D. Blunt and J.G. Metcalf, "Estimating Temporal Multipath via Spatial Selectivity: Building Environmental Knowledge into Waveform Design for Radar-Embedded Communications," *IEEE International Conference on Electromagnetics in Advanced Applications*, Turino, Italy, Sept. 14-18, 2009.

8. "Practical Aspects of Radar-Embedded Communications," *Waveform Diversity Workshop at Tri-Service Radar Symposium*, Boulder, CO, June 22-26, 2009.

9. "Radar-Embedded Communications," *Waveform Diversity Workshop at Tri-Service Radar Symposium*, Monterey, CA, June 23-27, 2008.

Research Collaborations

The following individuals have participated in the project through collaborative research efforts.

Dr. Michael Wicks (AFRL Sensors Directorate - retired)
Dr. Eric Mokole (NRL Radar Division)
Mr. Larry Cohen (NRL Radar Division)
Dr. Aaron Shackelford (NRL Radar Division)
Dr. Karl Gerlach (NRL Radar Division – retired)
Dr. Simon Watts (Thales UK)
Prof. Chris Baker (Ohio State University)
Prof. Hugh Griffiths (University College London)
Prof. Deb Chatterjee (University of Missouri – Kansas City)
Prof. James Stiles (University of Kansas)
Prof. Chris Allen (University of Kansas)
Prof. Erik Perrins (University of Kansas)
Prof. Sarah Seguin (University of Kansas)

Student Research Collaborations (as advisor)

Graduate Students
Mr. Thomas Higgins – currently pursuing PhD EE at KU
Mr. Matthew Cook – currently pursuing PhD EE at KU
Mr. Justin Metcalf – MSEE Fall 2011; currently pursuing PhD EE at KU
Mr. Casey Biggs – MSEE July 2009

Undergraduate Students
Ens. Michael Cribbs – Navy ROTC
Lt. Matthew Booth – Air Force ROTC
Mr. Austin Arnett – currently working on MSEE at KU